The Impact of Exercise Training on Conduit Artery Wall Thickness and Remodeling in Chronic Heart Failure Patients
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Abstract—Exercise training is an important adjunct to medical therapy in chronic heart failure, but the extent to which exercise impacts on conduit artery remodeling is unknown. The aim of this study was to evaluate the impact of aerobic and resistance exercise training modalities on arterial remodeling in patients with chronic heart failure. We randomized 36 untrained subjects with chronic heart failure to resistance training (58.8±3.5 years), aerobic training (61.3±2.8 years), or an untrained control group (64.4±2.4 years). Peak oxygen consumption during cycle ergometry increased after 12 weeks in both the resistance and aerobic training (P<0.001) groups, but not in controls, whereas leg strength only increased after resistance training (P<0.05). Brachial artery wall thickness decreased in the resistance training group (475±10 versus 443±13 μm; P<0.01), whereas no changes were apparent in the aerobic or control groups. Brachial diameter increased by about 6% and about 5% in the aerobic training and resistance training groups (P<0.01), with no change evident in the control group. The wall:lumen ratio consequently declined in the resistance training group at 12 weeks (0.121±0.004 versus 0.107±0.004; P<0.01) and increased in the control group (0.111±0.006 versus 0.121±0.009; P<0.05). No wall:lumen change was evident in the aerobic training group. Our findings suggest that exercise has a systemic impact on remodeling of conduit arteries in humans and that resistance exercise training may be advantageous in subjects with chronic heart failure in this regard. (Hypertension. 2011;57:56-62.)

Key Words: exercise • arteries • heart failure • remodeling • vasculature
of exercise on systemic changes in hemodynamics and wall shear stress.

Methods

Subjects

Thirty-six untrained subjects (32 men and 4 women; 61.5 ± 1.7 years) completed the study after screening, consisting of medical history and examination and hematologic and biochemical profile, including measurement of serum electrolytes, urea and creatinine, uric acid, liver function, and serum lipids. The following were excluded: smokers, those with renal impairment or proteinuria, hepatic impairment, hyperuricemia, hypercholesterolemia, exercise-induced ischemia, or hypertension. The study complied with the Declaration of Helsinki. The study protocol was approved by the Royal Perth Hospital Ethics Committee, and subjects provided written informed consent.

Subjects were randomized to 12 weeks of RT, AT, or control. All of the patients were stratified to New York Heart Association class I to III with an ejection fraction <50% and without congestive cardiac failure. Twenty-four subjects had coronary heart disease, 11 idiopathic dilated cardiomyopathy, and 1 noncompaction cardiomyopathy. Subject characteristics are presented in Table 1. Baseline medications (Table 2) were maintained for the duration of the study.

Experimental Measurements

Arterial wall thickness and diameter measurements, leg strength, and aerobic capacity were assessed at entry, with follow-up at 6 and 12 weeks. Ejection fraction and body mass index were obtained at entry and 12 weeks.

Brachial Artery Diameter and Wall Thickness Analysis

A 10-MHz multifrequency linear array probe attached to a high-resolution ultrasound machine (Aspen, Acuson) was used to visualize the brachial artery proximal to the cubital fossa. Perpendicular incidence of the B-mode imaging ultrasound beam in relation to the orientation of the vessel provided clearly demarcated intima-media boundaries, which were optimized using contrast controls on the ultrasound machine. The analog video output from the ultrasound machine was converted into a digital DICOM 3.0 file by DICOM Encoder software described by Potter et al. \(^23-25\) Heart rate and blood pressure were determined on the contralateral arm from an automated sphygmomanometer (Dinamap 8100, Critikon).

Arterial diameter and wall thickness were measured using DICOM-based intima-media diameter measurement software, after an overnight fast, as described previously. A custom-designed software performs edge detection and wall tracking that is independent of investigator bias. The software is written in an icon-based

### Table 1. Subject Characteristics at Baseline and 12-Week Follow-Up

<table>
<thead>
<tr>
<th>Characteristic of Subjects</th>
<th>Control (n=12)</th>
<th>Aerobic Trained (n=12)</th>
<th>Resistance Trained (n=12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>Pre 12 wk</td>
<td>Pre 12 wk</td>
<td>Pre 12 wk</td>
</tr>
<tr>
<td>Male gender</td>
<td>11</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>86.5 ± 4.0</td>
<td>87.6 ± 4.1</td>
<td>89.2 ± 4.5</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>30.1 ± 1.3</td>
<td>30.5 ± 1.3</td>
<td>30.4 ± 1.1</td>
</tr>
<tr>
<td>SBP, mm Hg</td>
<td>123 ± 6</td>
<td>121 ± 8</td>
<td>127 ± 4</td>
</tr>
<tr>
<td>DBP, mm Hg</td>
<td>69 ± 3</td>
<td>67 ± 4</td>
<td>74 ± 2†</td>
</tr>
<tr>
<td>Rest HR, bpm</td>
<td>63 ± 4</td>
<td>62 ± 3</td>
<td>67 ± 4</td>
</tr>
<tr>
<td>NYHA class</td>
<td></td>
<td></td>
<td>5.1 82.4 ± 0.6</td>
</tr>
<tr>
<td>I</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>II</td>
<td>6</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>III</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Etiology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IHD</td>
<td>9</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>ICM</td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>NC</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

BMI indicates body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate; EF, ejection fraction; NYHA, New York Heart Association; IHD, ischemic heart disease; ICM, idiopathic dilated cardiomyopathy; NC, noncompaction cardiomyopathy. Data are mean ± SEM.

*Data are significantly different from resistance-trained group at baseline (P<0.05).
†Data are significantly different from preintervention (P<0.05).

### Table 2. Cardiac Medication Use by Subject Grouping

<table>
<thead>
<tr>
<th>Class of Medication</th>
<th>Control</th>
<th>Aerobic Trained</th>
<th>Resistance Trained</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE inhibitor</td>
<td>9 (75)</td>
<td>12 (100)</td>
<td>9 (75)</td>
</tr>
<tr>
<td>Angiotensin II inhibitor</td>
<td>3 (25)</td>
<td>1 (8)</td>
<td>0</td>
</tr>
<tr>
<td>Furosemide</td>
<td>9 (75)</td>
<td>10 (83)</td>
<td>12 (100)</td>
</tr>
<tr>
<td>Spironolactone</td>
<td>5 (42)</td>
<td>6 (50)</td>
<td>9 (75)</td>
</tr>
<tr>
<td>Digoxin</td>
<td>1 (8)</td>
<td>5 (42)</td>
<td>3 (25)</td>
</tr>
<tr>
<td>Amiodarone</td>
<td>1 (8)</td>
<td>1 (8)</td>
<td>0</td>
</tr>
<tr>
<td>Aspirin</td>
<td>10 (83)</td>
<td>7 (58)</td>
<td>7 (58)</td>
</tr>
<tr>
<td>Warfarin</td>
<td>3 (25)</td>
<td>5 (42)</td>
<td>3 (25)</td>
</tr>
<tr>
<td>Clopidogrel</td>
<td>3 (25)</td>
<td>2 (17)</td>
<td>3 (25)</td>
</tr>
<tr>
<td>HMG-COA reductase inhibitor (statin)</td>
<td>10 (83)</td>
<td>6 (50)</td>
<td>7 (58)</td>
</tr>
<tr>
<td>β-blocker</td>
<td>10 (83)</td>
<td>12 (100)</td>
<td>11 (92)</td>
</tr>
<tr>
<td>Antianginal</td>
<td>5 (42)</td>
<td>4 (33)</td>
<td>0</td>
</tr>
</tbody>
</table>

ACE indicates angiotensin-converting enzyme; HMG-COA, 3-hydroxy-3-methylglutaryl-coenzyme A. Data are n (%).
Table 3. The Influence of Resistance and Aerobic Training on Aerobic Capacity and Leg Strength

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Aerobic Trained</th>
<th>Resistance Trained</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>6 wk</td>
<td>12 wk</td>
</tr>
<tr>
<td>VO\textsubscript{2} peak, mL·min\textsuperscript{-1}·kg\textsuperscript{-1}</td>
<td>15.1±1.3</td>
<td>14.5±1.2</td>
<td>14.1±1.1†</td>
</tr>
<tr>
<td>Exercise time, s</td>
<td>570±62</td>
<td>568±61</td>
<td>543±60‡</td>
</tr>
<tr>
<td>Peak HR, bpm</td>
<td>117±7</td>
<td>118±5</td>
<td>111±8</td>
</tr>
<tr>
<td>Limiting symptom, CPET</td>
<td>Dyspnea</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Leg fatigue</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Exhaustion</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Leg strength, kg</td>
<td>62±7</td>
<td>61±8</td>
<td>63±7</td>
</tr>
</tbody>
</table>

HR indicates heart rate; CPET, cardiopulmonary exercise testing, primary symptom at volitional exhaustion. Data are mean±SEM.
*Significantly different from pretraining at P<0.05.
†Significantly different from pretraining at P<0.01.
‡Significantly different from pretraining at P<0.001.

Assessment of Exercise Tolerance
Cardiopulmonary exercise testing was undertaken on a cycle ergometer (Corival, Lode), with initial workload set at 25 W and 25 W increments every 3 minutes. Heart rate and rhythm were continuously recorded by 12-lead ECG, and blood pressure was measured manually during the last 30 seconds of each stage by phymgomanometry. Time to volitional fatigue (seconds) was recorded, and VO\textsubscript{2} peak was determined by indirect calorimetry using the Vmax metabolic analysis system (Sensormedics).

Assessment of Muscular Strength
Maximal voluntary contractile strength was assessed using dual leg extension exercise using the 1 repetition maximum technique on a pin-loaded weight stack resistance machine (Pulsestar), with minimum 2.5-kg increments. Subjects were instructed in correct lifting technique and to avoid a Valsalva maneuver.

Exercise Training Interventions
Exercise trained subjects performed 3 supervised sessions per week at the Royal Perth Hospital Cardiac Gymnasium.

For the first 6 weeks of RT, weights were maintained at 50% to 60% 1 repetition maximum, and subjects worked on a 2:1 (60:30 seconds) work:rest ratio. For the second 6 weeks, weights were increased to 60% to 70% 1 repetition maximum with a 1:1 (45:45 seconds) work:rest ratio. Work:rest ratios were guided by an external auditory cue. After the first few sessions, subjects performed 3 sets of 9 exercises, with a 3-minute rest period between each set, for a total of 46.5 minutes per session.

AT commenced at 50% to 60% of baseline VO\textsubscript{2} peak and progressed to 60% to 70% of the VO\textsubscript{2} peak after 6 weeks, so that the relative intensity was consistent with the RT group. Exercise intensity was determined using the American College of Sports Medicine metabolic equations for walking and cycling and heart rate regression equations derived from the exercise tests at baseline for weeks 1 to 6 and at 6 weeks for weeks 7 to 12. After the first few sessions, each session involved 20 minutes of cycling and 20 minutes of treadmill walking separated by a 6.5-minute rest period to match the total duration of the RT group conditioning phase (46.5 minutes per session).

All of the exercise sessions were closely supervised by an experienced clinical exercise physiologist to ensure compliance with the exercise prescription. Control subjects were required to maintain their usual activities for the 12-week study period, but no formal exercise training was provided.

Statistical Analyses
Statistical analyses were performed using Excel (Windows Excel 2007) and SPSS version 15.0. All of the data are reported as mean±SEM, and statistical significance was assumed at P<0.05. All of the variables were analyzed using 2-factor general linear models with repeated measures. The factors were training status and group. Post hoc analysis was performed with the least significant difference test to correct for multiple comparisons.

Results
Impact of Exercise Training on Subject Characteristics
Of the initial 38 subjects who entered the study, 2 subjects dropped out, both from the RT group, 1 because of work commitments and the other because of a noncardiac illness. For subjects who completed the study, attendance at exercise training was provided.

Results
Statistical analysis was performed using Excel (Windows Excel 2007) and SPSS version 15.0. All of the data are reported as mean±SEM, and statistical significance was assumed at P<0.05. All of the variables were analyzed using 2-factor general linear models with repeated measures. The factors were training status and group. Post hoc analysis was performed with the least significant difference test to correct for multiple comparisons.

Results
Impact of Exercise Training on Subject Characteristics
Of the initial 38 subjects who entered the study, 2 subjects dropped out, both from the RT group, 1 because of work commitments and the other because of a noncardiac illness. For subjects who completed the study, attendance at exercise training was similar between the AT (85±3%) and RT (89±3%) groups. Table 1 presents selected characteristics of the 36 subjects who completed the study. Baseline ejection fraction and lumen diameter were slightly lower for the RT group compared with the control group (P<0.05), but there were no differences between groups for other parameters. Subjects were taking usual cardiac medications, and this was similar for all of the groups (Table 2).

Body weight and body mass index did not change in any of the groups across the 12-week intervention period.
Peak oxygen consumption increased after 12 weeks of AT ($P<0.001$) and 6 ($P<0.01$) and 12 weeks ($P<0.001$) of RT but decreased in controls ($P<0.01$) at 12 weeks. Leg strength only increased after 12 weeks of RT ($P<0.05$; Table 3).

**Impact of Exercise Training on Wall Thickness, Arterial Diameter, and Wall:Lumen Ratio**

Two-way ANOVA revealed significant interaction effects for change in wall thickness when both the control and RT ($P<0.001$) and control and AT groups were compared ($P<0.05$). Post hoc $t$ tests revealed significantly decreased wall thickness in the RT group at 12 weeks ($0.48\pm0.01$ versus $0.44\pm0.01$ mm; $P<0.05$), no change in the AT group ($0.49\pm0.02$ versus $0.485\pm0.02$ mm; $P=0.59$), and a slight increase in the control group ($0.49\pm0.17$ versus $0.53\pm0.02$ mm; $P<0.05$; Figure 1).

Brachial artery diameter (Figure 2) significantly increased by $\approx6\%$ (AT $4.30\pm0.19$ versus $4.56\pm0.2$ mm; $P<0.05$) and $\approx5\%$ (RT $3.98\pm0.16$ versus $4.17\pm0.16$ mm; $P<0.01$) after 12 weeks of training. No changes were evident in the control group ($4.51\pm0.19$ versus $4.52\pm0.24$ mm; $P=0.94$).

Significant interaction effects for change in wall:lumen ratio (Figure 3) were evident when both the control and RT ($P<0.001$) and control and AT groups were compared ($P<0.05$). Subsequent $t$ tests indicated that wall:lumen ratio declined significantly in the RT group at 12 weeks ($0.121\pm0.004$ versus $0.107\pm0.004$ mm; $P<0.01$) and increased significantly in the control group at 12 weeks ($0.111\pm0.006$ versus $0.121\pm0.009$ mm; $P<0.05$). No significant change was evident in the AT group ($P=0.20$).

**Discussion**

The purpose of the present study was to compare the impact of AT versus RT on remodeling of the brachial artery in subjects with CHF. Our principal finding was that RT increased artery diameter, decreased wall thickness, and consequently decreased the wall:lumen ratio of the brachial artery, whereas AT increased artery diameter without modifying wall thickness or wall:lumen ratio. This suggests that RT may be superior to AT in inducing remodeling of the brachial artery wall. In contrast to these benefits of exercise training, the control group exhibited an increased wall:lumen ratio and a trend for increased wall thickness across the 12 weeks of the study.

We contend that changes in brachial artery wall thickness, diameter, and wall:lumen ratio are indicative of systemic vascular remodeling, given that the upper limbs were not heavily involved in the exercises undertaken. It is likely, therefore, that systemic hemodynamic responses to bouts of exercise, which, in turn, modulate shear stress, a known stimulus to arterial wall remodeling,14–16,18,26 may have mediated these changes. In this sense, changes in the brachial artery provide an index of systemic arterial remodeling in response to exercise training, and RT may be a more...
beneficial modality in subjects with CHF to improve artery wall thickness.

Several cross-sectional studies have assessed artery wall thickness responses to exercise training in the lower limbs. AT was independently associated with decreases in femoral wall thickness in postmenopausal women. Similarly, healthy, aerobically trained men had larger femoral artery lumen diameter, smaller femoral wall thickness, and smaller wall:lumen ratio compared with sedentary men. Although a recent study found that femoral wall thickness increased with age, even in habitually exercising adults, smaller wall thickness was observed in the femoral artery of middle-aged and older adults who performed regular aerobic exercise. In one of the few longitudinal studies, 3 months of lower limb AT developed larger common femoral artery lumen diameters, smaller femoral artery lumen diameters, and smaller wall:lumen ratios in healthy but sedentary middle-aged men. Collectively these studies suggest that exercise may retard age-related wall thickening as a localized effect.

Studies of exercise training on carotid artery thickness have been equivocal. A decrease in carotid artery wall thickness occurred in overweight and obese children, after 6 and 12 months of exercise training, suggesting a systemic effect; however, no change was evident after exercise training in healthy adults.

Our data indicate that exercise training predominantly involving the lower limbs can decrease brachial artery wall thickness and wall:lumen ratio in patients with existing cardiovascular disease. Limited previous evidence suggests that leg exercise training can increase peak vasodilator capacity, an index of resistance vessel remodeling, in the upper limbs following a training regimen specifically involving the legs and changes in peak brachial artery diameter and flow in response to predominantly lower limb exercise training. Finally, we recently identified beneficial effects on conduit artery wall thickness and wall:lumen ratio in both upper and lower limbs of healthy sedentary subjects who undertook 24 weeks of exercise training. However, our present data are the first, to our knowledge, to suggest that arterial wall remodeling can occur as a systemic response to exercise training in CHF subjects and the first to compare the impact of exercise training modalities.

We observed a superior effect of RT to induce remodeling of the brachial artery wall compared with AT. The mechanisms responsible for changes in wall thickness in response to training were not specifically addressed in this study, but the similar magnitude of improvement in aerobic capacity in both training groups (19% versus 20%) suggests that change in fitness, per se, is not primarily responsible for arterial remodeling. Similarly, there were no differences between the AT and RT group in terms of change in body mass index or BP, arguing against a unique effect of RT on arterial remodeling mediated through changes in these cardiovascular risk indices. Exercise is known to increase arterial shear stress, a potent stimulus to increased endothelium-derived NO production and consequent arterial remodeling in animals. It is possible that exercise-mediated changes in hemodynamics and shear stress, which can occur in the brachial artery during leg exercise, may transduce systemic changes in arterial caliber and wall thickness. We recently observed differences in brachial artery shear stress with different forms of leg exercise; similarly, RT may have elicited a different shear stress–transducing stimulus to AT in the present study.

Systemic conduit artery remodeling may have implications for changes in arterial compliance and atherosclerotic risk. Indeed, brachial artery wall thickness predicts cardiovascular events in patients with and without angiographic evidence of atherosclerosis and is associated with the severity of atherosclerosis in the carotid and coronary arteries. In CHF, brachial wall thickness progressively increases with worsening disease severity. If remodeling is extrapolated to the resistance vessels responsible for determining afterload, our data may have implications for the optimal exercise management of patients with CHF. Our results, therefore, endorse the use of carefully prescribed and administered RT as a modality in this clinical population.

This study benefited from a longitudinal study design and randomization of subjects to exercise and inactive control groups. We also used custom-designed edge-detection and wall tracking software program that is operator independent and has been validated against an external phantom. The exercise training that we undertook was individually prescribed and closely supervised. We made a concerted effort to ensure that forearm muscle
work was minimized during the exercise programs, so that brachial
measures could be used as markers of systemic exercise effects. A limitation of the study was the lack of
a combined AT and RT group, and it is possible that such
an intervention may be associated with benefits exceeding
those observed in the present study. Our findings are
limited to subjects with CHF, and we did not assess carotid
or lower limb arterial wall changes, which may have
provided information pertaining to the impact of localized
exercise and the potential benefit in terms of cardiovascular
risk. Finally, it is possible that AT may have induced
wall changes if a longer program had been completed.

Perspectives
We assessed artery wall thickness, lumen diameter, and
wall:lumen ratio in the brachial arteries of patients with CHF
who undertook either RT or AT. Our rationale for studying
the brachial artery was that this artery reflects systemic
arterial remodeling, a process that may depend on episodic
changes in hemodynamics and arterial shear stress. Our
findings suggest that exercise has a systemic impact on the
remodeling of conduit arteries in humans and that RT may be
a more beneficial training modality in subjects with CHF in
this regard.

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Australian Research Council.

Disclosures
None.

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